



PRES

NASA In-Space Manufacturing Technology

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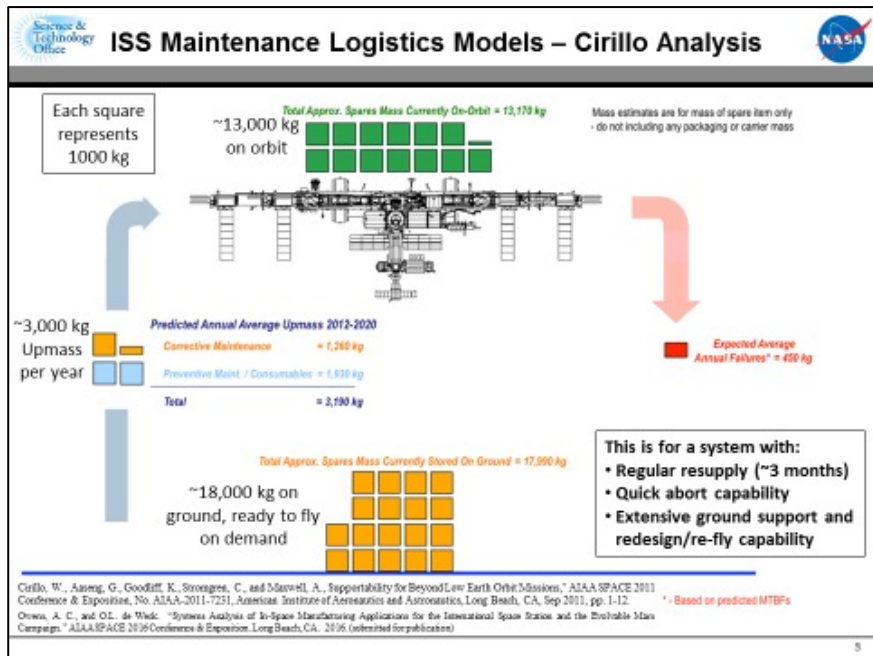


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ACS FALL 2021

RESILIENCE OF CHEMISTRY

Drivers -- The Case for ISM

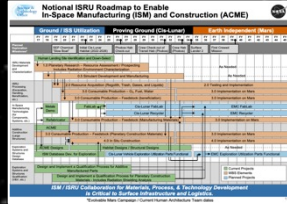


Current maintenance logistics strategy **will not be effective** for deep space exploration missions

Benefits from Incorporation of ISM

ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability



Historical Reference



NASA was not the first to understand and utilize the benefits of processing materials in a microgravity environment.

That honor likely goes to William Watts of Bristol, England who in 1753 built a “drop tower” to process molten lead into uniformly spherical shot for firearms



Boughton Shot Tower
Chester, England
1799, 168' tall



Molten lead is poured



Through a sieve



Uniform drops freefall (microgravity), buoyancy effects are minimized

Surface tension dominates forming uniform spheres



Solidified shot lands in a cushion of cooling water



Phoenix Shot Tower
Baltimore, MD, 234' tall
1828, tallest structure in US
2.5 million pounds shot/year

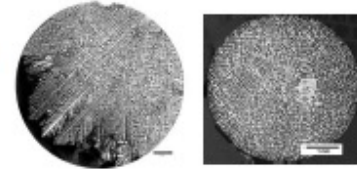
Credit: Richard Grugel, NASA

Microgravity and Physical Phenomena



Gravity drives thermal and solutal convection

- Detrimently impacts solidification microstructures
- Compromises diffusion studies



Gravity responsible for sedimentation/buoyancy

- Promotes non-uniform particle distributions

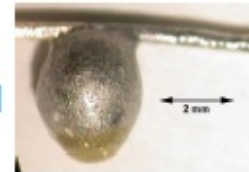


Gravity necessitates, usually, a container to process/study liquids

- Compromises accurate study of material properties such as viscosity
- Compromises nucleation/undercooling studies

Gravity overwhelms subtle physical features

- Thermocapillary effects, surface tension are masked

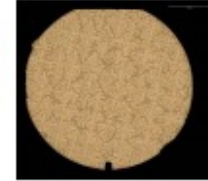


Microgravity and Physical Phenomena



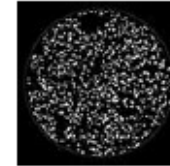
Microgravity minimizes thermal and solutal convection

- Promotes diffusion controlled growth and uniform solidification microstructures



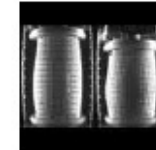
Microgravity minimizes sedimentation / buoyancy

- Promotes uniform particle distributions
→ Advances our understanding of coarsening and sintering



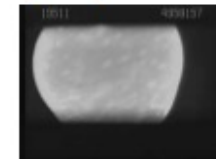
Microgravity minimizes pressure heads

- Reduces defects in semiconductor materials
- Allows study of granular materials



Microgravity eliminates a container to process / study liquids

- Improves accuracy of material properties measurements such as viscosity and surface tension
- Facilitates nucleation studies



Microgravity Platforms



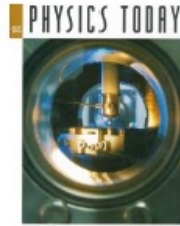
Drop Towers



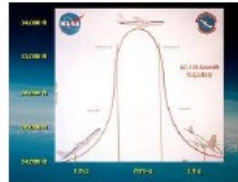
**Glenn
Research
Center
432'**

~5.2s μ g

Levitators



Parabolic Aircraft



~30s μ g

Sounding Rockets



15-25 min μ g

Space Vehicles / Stations

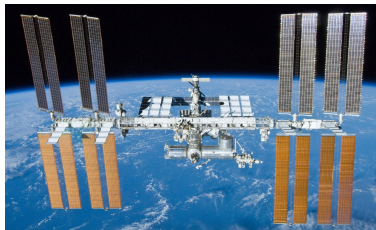


Long duration μ g

The Vision of Space Sustainability



Manufacturing in space is a destination-agnostic capability and has clear mission benefits beyond low earth orbit, where cargo resupply opportunities become more limited. These technologies are key enablers for sustainable space exploration.



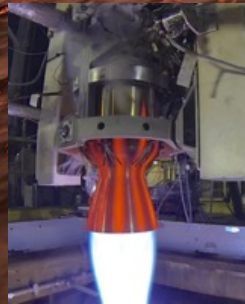
ISS is the testbed for ISM.



ISM capabilities demonstrated on ISS are applicable to Gateway and the lunar surface.



Additive Manufacturing at NASA



For Space



In Space



On-orbit servicing,
assembly, and
manufacturing (OSAM)

Image from Made in Space



Planetary Surface
Construction

Image from Icon and SEArch+

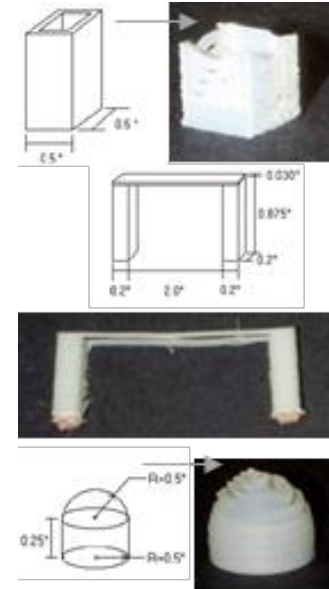
In-Space Manufacturing at NASA – the Beginning

- First “proof of concept” experiment to assess whether a Stratasys FDM would function in a microgravity environment was conducted on NASA’s KC-135 reduced-gravity aircraft in 1999.
- Seven part configurations were designed, built using acrylonitrile butadiene styrene (ABS) feedstock, and analyzed.
- Initial experiment results indicated that “application of layered fabrication techniques is apparently feasible for standard and some non-standard part designs.”
- It was recommended that “further testing be granted in a full microgravity setting, i.e. aboard the space shuttle or space station”
- A new opportunity arose in 2004 as NASA’s Office of Biological and Physical Research (OBPR) was restructuring its portfolio to increase focus on support for exploration.

The Exploration Science and Technology Division at MSFC formulated and recommended the establishment of the In Situ Fabrication and Repair (ISFR) Program Element



PI Ken Cooper on KC-135



Examples of parts
“as-designed vs as-built”

Constraints Removed by Manufacturing in Space

Constraint ¹	Constraint removed by ISM?
Structures must be designed for launch loads.	ISM enables structures which are optimized for operation in space, not for launch loads.
Structures must fit within launch vehicle payload fairings.	ISM enables structures whose size is limited only by the fabrication volume of the ISM capability.
Materials must be disposed of at the end of their lifecycle.	Materials can be recycled and used for further manufacturing.
All the spare parts and equipment needed for on-orbit servicing or repair and replacement activities must be prepositioned.	Spare parts can be made on-demand. ISM capabilities can enable on-orbit servicing and repair of equipment.
Component reliability and redundancy (R&R) largely driven by mission life/duration.	Redundancy is augmented by ISM capability to make components on demand. R&R requirements may be reduced in some instances when an ISM capability is present.

Paradigm shift

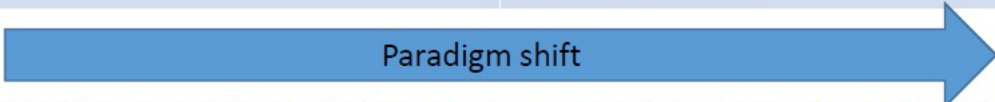


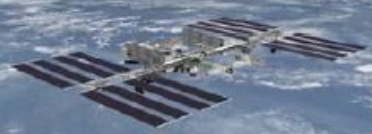
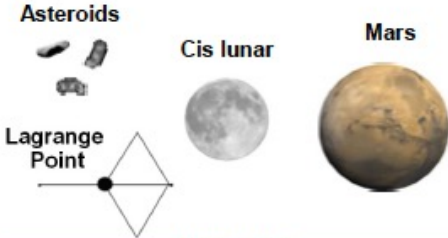


Table adapted from Matthew Moraguez. "Technology Development Targets for In-Space Manufacturing." Master's Thesis. MIT, 2018.

In-Space Manufacturing Roadmap

Earth-based	Demos: Ground & ISS		Exploration Missions	
 <p>3D Print Plastic Printing Demo</p> <p>Material Characterization</p>	 <p>3D Print Plastic Printing Demo</p> <p>Material Characterization</p>	 <p>Recycler Mat. Char. Utilization Testing AMF</p> <p>Metal Printing FabLab Self-External Repair/Replicate Mfg.</p>	 <p>Asteroids</p> <p>Lagrange Point</p> <p>Cis lunar</p> <p>Mars</p>	
Pre-2012	2014	2015-2017	2018 - 2024	2025 - 2035+
Ground & Parabolic centric: <ul style="list-style-type: none"> Multiple FDM Zero-G parabolic flights Trade/System Studies for Metals Ground-based Printable Electronics/Spacecraft Verification & Certification Processes under development Materials Database CubeSat Design & Development 	<ul style="list-style-type: none"> ISS 3DP Tech Demo: First Plastic Printer on ISS NIAC Contour Crafting NIAC Printable Spacecraft Small Sat in a Day AF/NASA Space-based Additive NRC Study ISRU Phase II SBIRS Ionic Liquids Printable Electronics 	<ul style="list-style-type: none"> 3DP Tech Demo Add. Mfctr. Facility (AMF) ISM Certification Process Part Catalog ISS & Exploration Material & Design Database External Manufacturing Autonomous Processes Future Engineers Additive Construction 	ISS: Multi-Material FabLab EXPRESS Rack Test Bed (Key springboard for Exploration 'proving ground') <ul style="list-style-type: none"> Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics, embedded electronics, autonomous inspection & part removal, etc. In-Space Recycler Tech Demo ACME Ground Demos 	Cislunar, Lagrange FabLabs <ul style="list-style-type: none"> Initial Robotic/Remote Missions Provision feedstock Evolve to utilizing in-situ materials (natural resources, synthetic biology) Product: Ability to produce, repair, and recycle parts & structures on demand; i.e. "living off the land" Autonomous final milling
				Planetary Surfaces Points FabLab <ul style="list-style-type: none"> Transport vehicle and sites would need FabLab capability Additive Construction & Repair of large structures
				Mars Multi-Material FabLab <ul style="list-style-type: none"> Provision & Utilize in-situ resources for feedstock FabLab: Provides on-demand manufacturing of structures, electronics & parts utilizing in-situ and ex-situ (renewable) resources. Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.
ISS Serves as a Critical Exploration Test-bed for the Required Technology Maturation & Demonstrations				



In-Space Manufacturing (ISM) Overview



Project Description:

- The In-Space Manufacturing (ISM) portfolio provides a solution for sustainable, flexible missions through on-demand fabrication, replacement, and recycling capabilities.
- The ISM portfolio includes three GCD projects: (1) On-Demand Metal Manufacturing (ODMM); (2) On-Demand Manufacturing of Electronic components (ODME); and (3) Recycling and Reuse (RnR). ISM also includes a demonstration of 3D printing with regolith (Regolith Print), funded by HEOMD AES.

S&T Role:

- Project Management

Customer(s):

- Game Changing Development (GCD) - STMD
- Advanced Exploration Systems (AES) – HEOMD
- ISS, industry and academic partners



Image 1: Flexible printed sensor



Image 2: Techshot Fabrication Laboratory (FabLab)

ISM seeks to provide a meaningful capability for on-demand manufacturing during exploration missions. ISM must continue to test manufacturing technologies on the ISS and influence future exploration systems design.

On-Demand Manufacturing of Electronic Parts (ODME)



Project Objectives:

- Create a system or manufacturing suite as a demo on ISS capable of manufacturing a set of selected electronic devices on demand in microgravity.
- Develop and deliver for flight an ISM multiple-material system that can fabricate selected electronic devices on demand in microgravity.
- Demonstrate the ISM system is capable of fabricating and functionally verifying selected electronic devices aboard the ISS.

FY20-21 Milestones:

- Demonstrate thin film printing
- Deliver beta version Sensor Platforms
- Demonstrate integrated thin film deposition
- Deliver ground demo version of AstroSense

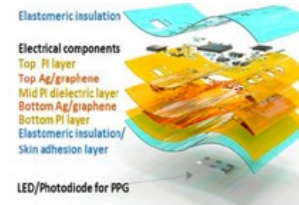


Image 1: Nano Fabricated thin film stack work with Georgia Tech



Image 3: Photo sintered Copper heater capable of 40C heating

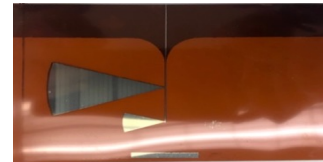


Image 5: Printed power harvesting antenna

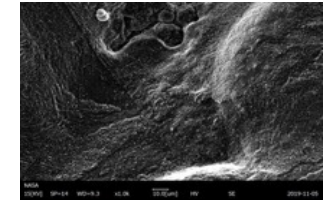


Image 2: In situ laser sintered Ti64

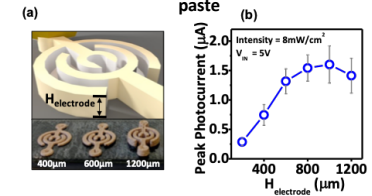


Image 4: Printed UV sensor

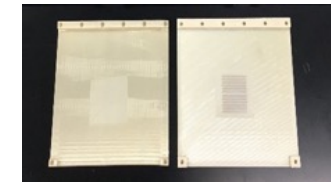


Image 6: REALM Quarter Wave Antennas

ODME is developing printed electronics, sensors, and power devices for a microgravity print demonstration on ISS in FY24. The planned technology demonstration article will be a wireless wearable sensor device for astronaut crew health monitoring. This device will ensure consistent health monitoring for extended missions to the Moon and Mars.



On-Demand Manufacturing of Mechanical Parts (ODMM)

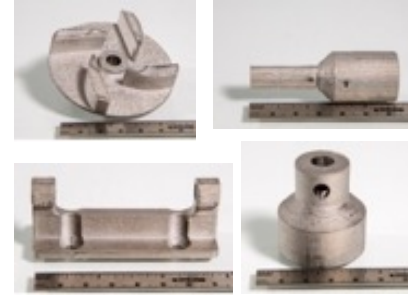


Project Objectives:

- Design, build, and demonstrate an on-demand manufacturing approach in low gravity for metal parts.
- Deliver to ISS a flight-certified, on-demand manufacturing system or systems.
- Demonstrate the manufacture of metal parts in a low-gravity environment on ISS.
- Evaluate parts made on ISS against parts produced on the ground.
- Develop physics-based models to predict processing parameters and material outcomes under low-gravity conditions for metals.

FY20-21 Milestones:

- Techshot Fabrication Laboratory BAA Phase A report
- Vulcan Engineering Development Unit (EDU) complete
- FabLab Micro-Furnace Prototype Testing
- Vulcan Interface Requirements Baseline (IRB)



Images 1-4: Parts printed with Techshot FabLab system. Clockwise from top left: arthoscopy cannula housing, clutch adapter, hinge base, impeller.

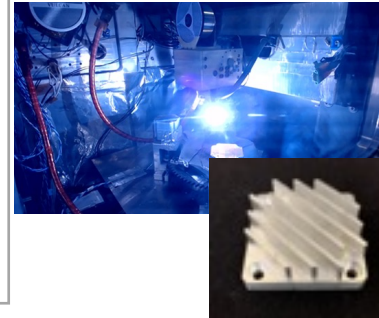
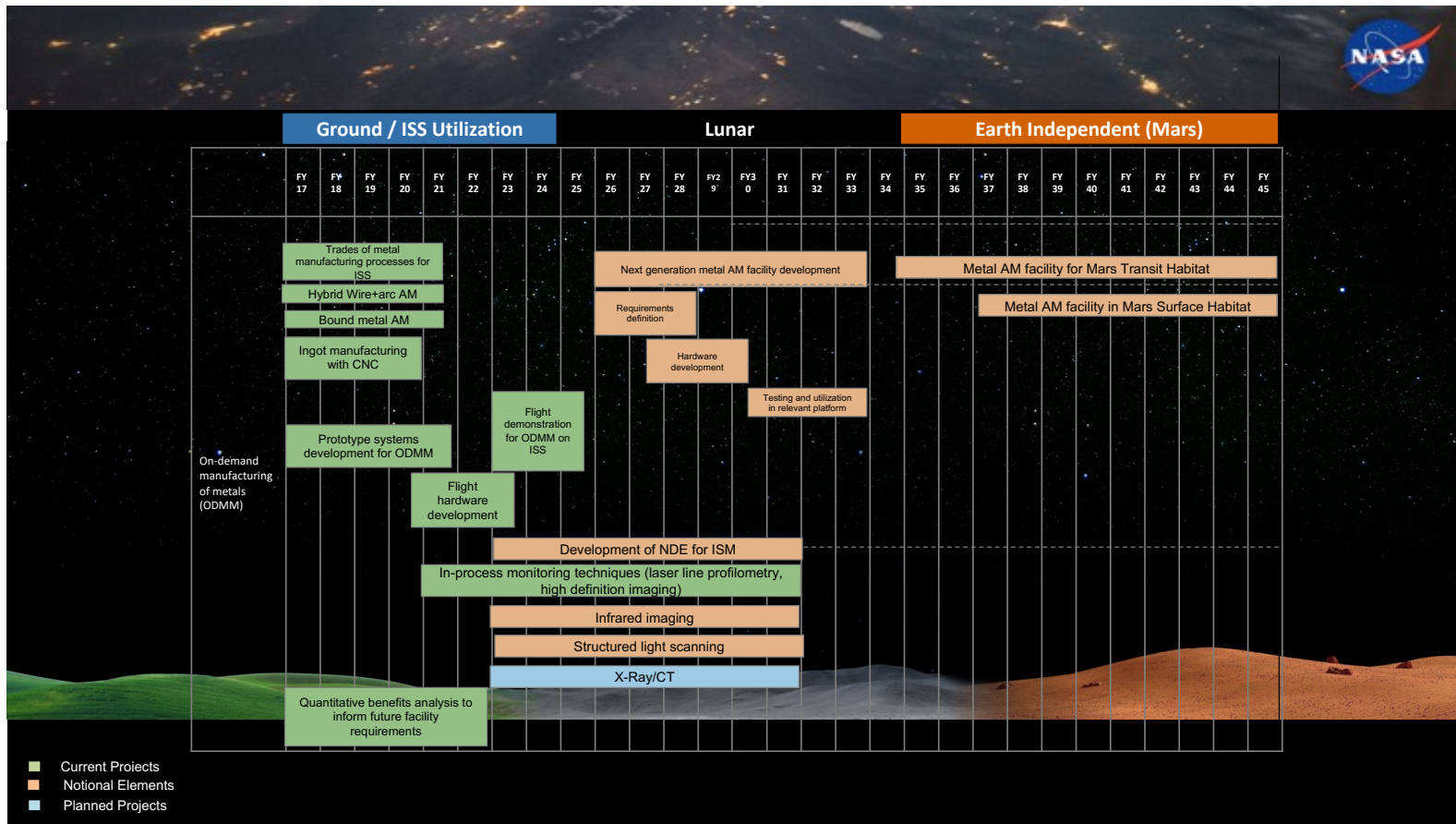


Image 5 and 6: Made in Space Vulcan in operation and heat sink produced with system.

ODMM focuses on development of metal additive manufacturing technologies for ISS demonstration, with a goal of evolving these systems for future orbital platforms, transit habitats, and the lunar surface. ODMM will reduce logistics requirements for long-duration missions and potentially enhance crew safety by enabling a more rapid response to unforeseen scenarios.

On-Demand Manufacturing of Metals (ODMM) Roadmap





The Recycling and Reuse (RnR) project element is developing materials and recycling technologies with the goal of developing an ecosystem capable of repurposing waste products, such as packaging materials and defective components, into feedstock for manufacturing. This will help enable long-duration space missions by reducing costs and logistics while increasing reliability.

The 3D Printing in Zero G Technology Demonstration Mission (2014)



The 3DP in Zero G Tech Demo delivered the first 3D printer to ISS and investigated the effects of consistent microgravity on fused deposition modeling

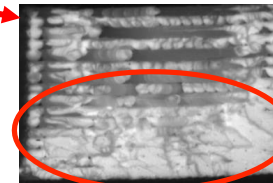
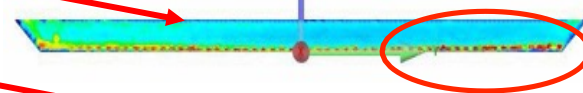
Phase I Prints (Nov-Dec 2014): mechanical property test articles; range coupons; and functional tools



Printer inside Microgravity Science Glovebox (MSG)

Key Observations:

- Tensile and Flexure: Flight specimens stronger and stiffer than ground specimens
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend
- Structured Light Scanning: Protrusions along bottom edges (more pronounced for flight prints)
- Microscopy: Greater Densification of Bottom Layers (flight tensile and flexure)



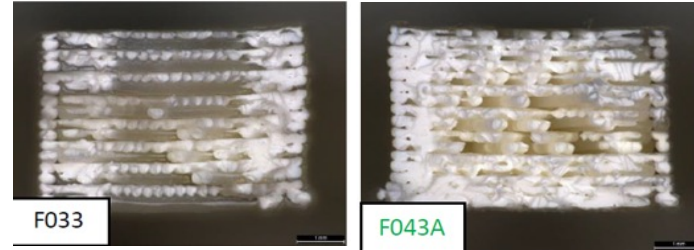
Conclusions

- Z-Calibration distance variation suspected to be primary factor driving differences between flight and ground samples
- Potential influence of feedstock aging are being evaluated further

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)



- Phase II Prints:
 - 25 specimens (tensile + compression) built at an optimal extruder standoff distance.
 - 9 specimens printed with intentionally decreased extruder standoff distance to mimic Phase I flight process conditions
- Key findings:
 - No substantive chemical changes in feedstock
 - No evidence of microgravity effects noted in SEM, SLS, CT analysis. Some internal structure variation between builds and with changes in process settings (primarily compression)
 - All prints to date with 3DP appear to be broadly part of the same family of data
 - Phase I data variations appear traceable to:
 - Differences in manufacturing process settings (extruder standoff distance)
 - Data scatter - characteristic of many additively manufactured materials and processes.
 - Printer variability

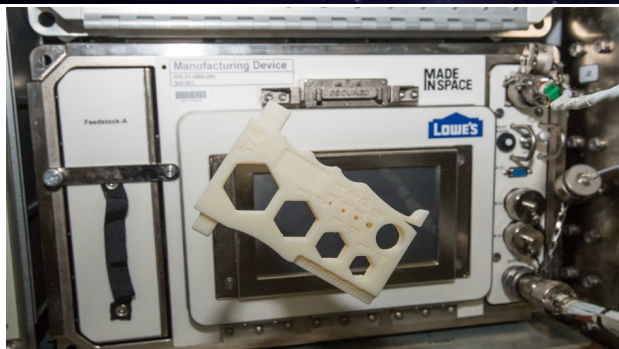


Cross-section of PII tensile specimen manufactured at optimal extruder setting (left) compared with specimen manufactured at a reduced extruder standoff distance (right). Right image has a cross-section characteristic with PI flight prints.

Specimen set	Average ultimate tensile strength (KSI)	Coefficient of variation
Phase II	3.68	6.71
Phase II optimal	3.63	6.61
Phase II off-suboptimal	3.93	0.07
Phase I ground	3.46	1.71
Phase I flight	4.04	5.95

Overall, we cannot attribute any of the observations to microgravity effects.

ISM Utilization and the Additive Manufacturing Facility: Material Characterization and Example Functional Parts



AMF on ISS with printed multi-purpose tool floating in front (photos courtesy of MIS)

- Additive Manufacturing Facility (AMF), the second generation printer, is a commercial, multi-user facility developed by Made in Space, Inc.
- Upgrades beyond 3DP include:
 - a) Print with multiple material (ABS, ULTEM 9085, and HDPE)
 - b) Integral cameras/sensors for automated monitoring
 - c) Maintenance procedures reduce crew time
 - d) Leveling and calibration with on-board systems
- Materials characterization task developing baseline mechanical properties on ABS (test matrix below)



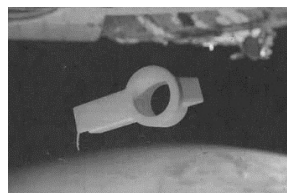
SPHERES Tow Hitch



Antenna Feed Horn



REM Shield Enclosure



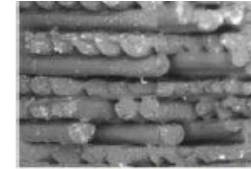
OGS AAA Adapter

AMF Mechanical Property Test Matrix				
Type, Orientation	Qty (ground)	Quantity (flight)	ASTM #	Properties
Tension, 0	10	10	D638	Modulus, strength, strain, Poisson's
Tension, 90	10	10	D638	Modulus, strength, strain
Compression, 0	10	10	D695	Modulus, "strength," strain
Compression, 90	10	10	D695	Modulus, "strength," strain
Tension, +/-45 (shear)	10	10	D3518	Modulus, strength, strain, Poisson's
Flatwise tension	10	10	C297	z-direction (through-thickness) tensile strength
Range coupon	2	2	n/a	n/a
EMU fan cap	1	1	n/a	n/a
Total	63	63		

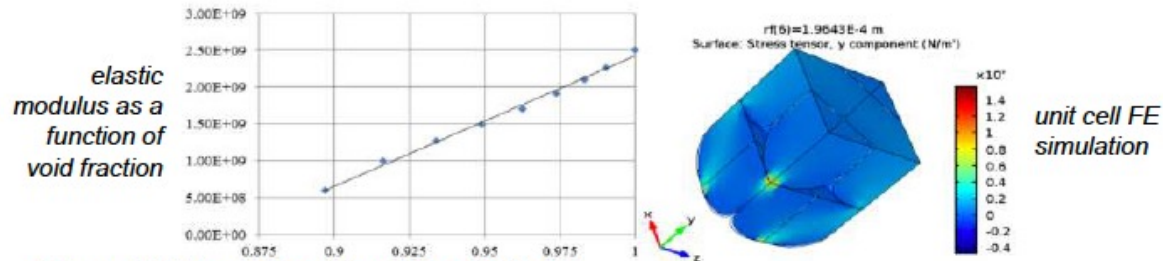
Modeling Work on FDM (NASA ARC)

Structural Modeling of Macroscopic FDM parts

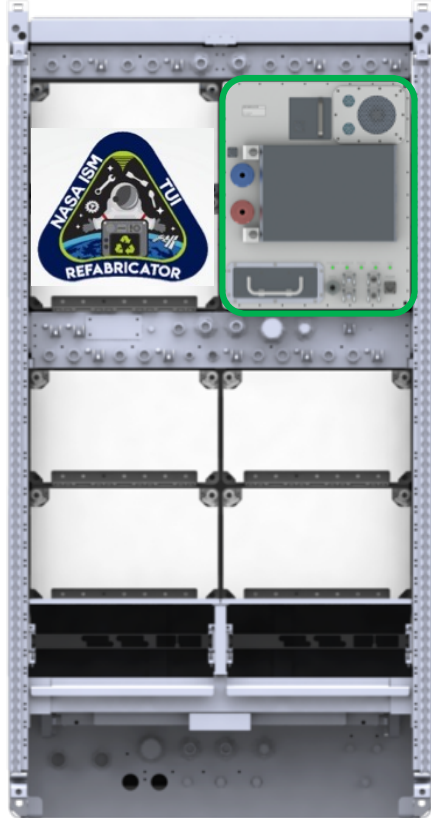
- Modeled FDM parts as a composite cellular structure with known microstructure (as determined from the deposition process model)
- Effective structural parameters of the part were studied analytically based on classical homogenization and laminate theories
- Developed a finite-element model in ABAQUS to estimate the elastic moduli of representative volume elements or unit cells in order to verify analytical models
- Moduli were simulated for different layups, raster orientations, air gap distribution as a function of volume void fraction
- The part strength was estimated using the Tsai-Wu failure criterion



*representative
volume element*



In-Space Recycling & Reuse: ISS Refabricator Closing the Manufacturing Loop



Mission Goal of Refabricator

Demonstrate how the integrated polymer Recycler/3D Printer can increase mission sustainability by providing a repeatable, closed-loop process for recycling plastic materials/parts in the microgravity environment into useable feedstock for fabrication of new and/or different parts.

- Technology Demonstration Mission conducted under SBIR contract with Tethers Unlimited, Inc. (TUI)
- Refabricator is an integrated 3D printer (FDM) which recycles ULTEM plastic into filament feedstock through a novel TUI process which requires no grinding.
- Designed to be self-contained and highly automated.
- Installation and activation on the ISS EXPRESS Rack on 2/14/19



**Refabricator
(Top) and
Printed
Parts
(Bottom)**

The 1st Generation Exploration Recycler will include a 3D Printer, Recycler, and dry-heat Sterilizer to fabricate and recycle polymer parts, including food and medical-grade items which make up a high percentage of trashed materials on the ISS. This effort is underway through a Phase II SBIR entitled “ERASMUS” with TUI. Refabricator design and testing is informing the ERASMUS activity.

- ISM is working with the AES Logistics Reduction (LR) team at JSC for application cases.
- TUI digitally reconstructed the NASA-provided urine funnel drawing and made adaptations in order to better support its manufacturability.
- ERASMUS also addresses food (i.e. spoon), medical device (i.e. otoscope specula, finger splint), and specimen production.
- Prototypes are provided to the JSC Logistics Reduction team for further testing and analyses.
- Next Steps:
 - Evaluate process-induced degradation and re-use capabilities.
 - Develop a medical device 3D printing and sanitization process.
 - Part production and customization.
 - Breadboard-level verification of the complete ERASMUS process.



Printed, Recycled, Sanitized
Urine Funnels



Printed, Recycled, Sanitized
Spoons



Voronoi Patterned Finger
Splint

Common Use Materials Development - Recyclable Materials: SBIR Activities



- Logistics analyses indicate a dramatic impact of recycling capability to reduce initial launch mass requirements for long duration missions
 - Current packaging materials for ISS represent a broad spectrum of polymers: LDPE, HDPE, PET, Nylon, PVC
- Tethers CRISSP (Customizable Recyclable ISS Packaging) seeks to develop common use materials (which are designed to be recycled and repurposed) for launch packaging (Phase II-E SBIR)
 - Recyclable foam packaging made from thermoplastic materials using FDM
 - Can create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties
- Cornerstone Research Group (CRG) is working under a Phase II-E SBIR on development of reversible thermoset copolymer materials
 - Designs have strength and modulus values comparable to or exceeding base thermoplastic materials
 - Maintains depressed viscosity so that materials are compatible with FDM



CRISSP packaging (image from Tethers Unlimited)



FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from CRG)

In-Space Metal Additive Manufacturing Capability: SBIR Activities



- Made in Space Vulcan unit (Phase II SBIR)
 - Integrates FDM head derived from AMF
 - Wire and arc metal deposition system
 - CNC end-mill for part finishing
- Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (Phase II SBIR)
 - Uses sound waves to consolidate layers of metal from foil feedstock
- TUI MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly) (Phase II SBIR)
 - Ingot-forming method to process virgin or scrap metal.
 - Builds on Refabricator recycling process
 - Bulk feedstock is CNC milled
- Techshot, Inc. SIMPLE (Sintered Inductive Metal Printer with Laser Exposure) (Phase II-E SBIR)
 - AM process with metal wire feedstock, inductive heating, and a low-powered laser



Illustration of Vulcan Exterior Unit (image courtesy of Made in Space)

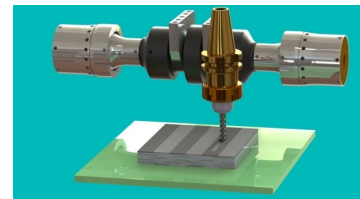
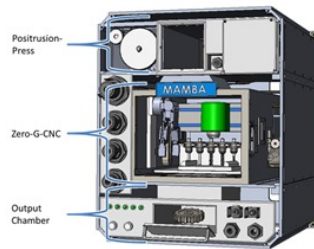
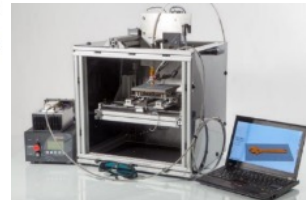


Illustration of UAM process (image courtesy of Ultra Tech)



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.



Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.

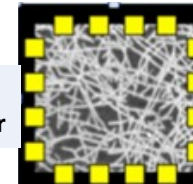
Multi-Material Fabrication With Printed Electronics



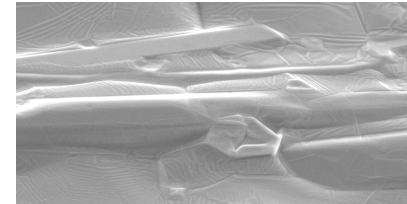
- Objective: Evaluate and develop technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions.
- Working with multiple NASA centers, industry (including small businesses), academia, and Other Government Agencies (OGAs).
- Sensor Development:
 - Piezoelectric/pyroelectric-based combination pressure/temperature sensor.
 - Wearable RFID sensors.
 - Sensors to detect NH_3 , CO_2 , CO , CH_4 , H_2 , and humidity.
- Ink Development
 - Inconel 718
 - Aluminum and Aluminum-tin
 - Palladium-silver electrode ink
- Develop power sources to run the sensors and store energy (supercapacitors) to build a self-contained system.
- Develop Flexible Electronics Sensors including the development of a flexible sensor circuit with flexible components



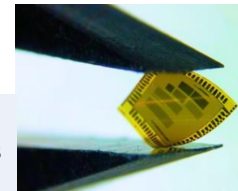
ECLSS
Composite
Pressure/
Temperature
Sensor



Gas
Sensor



Sintered Inconel 718 Ink

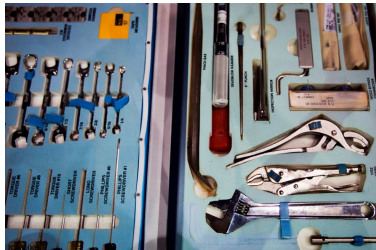


Flexible
Electronics
Sensors

What Do We Need to Make on Space Missions

The in-space manufacturing design database is a digital catalog of parts which represent candidates for on-demand manufacturing with ISM platforms.

- Database consists of hundreds of parts from environmental control and life support systems (ECLSS), crew tools, medial toolkit, communications systems, electrical power systems, and other payloads
- While some parts use polymeric materials (or could be made of a polymer if launch constraints are removed), most candidate parts for ISM are metal
- Analysis of a database of spares for ISS environmental control and life support systems showed that approximately 50% of ECLSS spares could be manufactured in a 150mm x 150 mm x 150 mm build volume (considers part volume only and not other attributes of manufacturability)¹
- Key technology gap for manufactured part use is on-orbit inspection capabilities



Examples of crew tools from space shuttle. Image from NASA.



Urine processor distillation assembly. Image from NASA.

NextSTEP Multi-Material Fabrication Laboratory (FabLab)



DESIGN Phase A (18 months)

Goal: Demonstrate a scalable ground-based PROTOTYPE of an ISM FabLab System to mature into flight demonstrations on the ISS within three years.

BUILD Phase B (12 months)

Goal: Mature the Phase A ISM FabLab System prototype into a flight integration deliverable. Phase B criteria and needed path are informed by Phase A results and will be released under a follow-on BAA.

FLY Phase C (18 months)

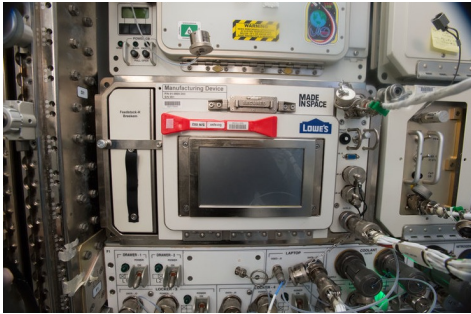
Goal: Demonstrate the capability of a Phase B ISM FabLab System on the ISS and evaluate risk. Phase C criteria are informed by Phase B results and will be released as a follow-on BAA or other acquisition vehicle.

- NASA solicited proposals for the development of a Multi-Material Fabrication Laboratory (FabLab) capable of end-to-end manufacturing of precision parts for sparing, repair, and logistics support. during space missions.
 - ◆ High degree of autonomy
 - ◆ On-demand manufacturing of metallics and other materials in the microgravity environment
 - ◆ Minimum build envelope of 6"x6"x6"
 - ◆ Earth-based remote commanding
 - ◆ In-line remote/autonomous inspection and quality control
- This is the first step toward a fully-integrated, on-demand manufacturing capability that is able to produce finished, ready-to-use metallic, plastic, and/or electronic products during Exploration missions.

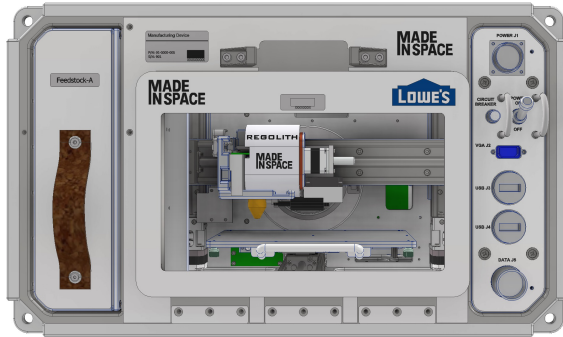
3D Printing and In Situ Resource Utilization (ISRU): RegISS demonstration



RegISS will be an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It will be the first demonstration of manufacturing with ISRU-derived feedstocks on ISS.



Made in Space (MIS) owns and operates the Additive Manufacturing Facility (AMF).



In this effort, a previously flown version of AMF will be modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.



Printing (top) and testing (bottom) of a compression cylinder with a regolith simulant/polymer feedstock.

NASA's Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) Project



The goal of MMPACT is to develop, deliver and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms and blast shields using lunar-regolith based materials.

- Partnership between NASA, ICON, SEArch+, and Department of Defense
- Three project elements:
 - Olympus – autonomous construction system
 - Construction feedstock materials development
 - Microwave Sintering Construction Capabilities (MSCC)



Image from ICON/Search+

ISM Lessons Learned



1	Importance of a locked manufacturing process for flight operations and process control
2	Importance of maintaining appropriate insight into contractor activities and hardware development which may require flight-like hardware at NASA
3	Utility of ISM technologies in a mission scenario will be severely limited by a lack of inspection capabilities such as NDE.
4	Need for accurate logistics analysis on ISM benefits which considers constraints of materials, manufacturing systems, and capabilities of these systems
5	Ability to explore use scenarios of ISM operations on ISS which is now limited by ISS constraints on crew time and crew interaction with systems
6	Infusion of ISM into future platforms will require early coordination/integration with designers of future systems <i>and</i> design of future systems for accessibility and maintainability
7	Limited specimen sets which can be produced on ISS and lack of NDE can make part certification difficulty.
8	Power and safety are biggest challenges to implementing metal AM on ISS
9	Need for shift in crew roles on future missions so the crew can operate manufacturing systems during communications black-out
10	ISM has a clear mission pull for Mars, but we also need clear buy-in for lunar architectures as a proving ground for Mars



Technology Drives Exploration

Thank You!

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